

Field O stars: formed *in situ* or as runaways?

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ABSTRACT

A significant fraction of massive stars in the Milky Way and other galaxies are located far from star clusters and star-forming regions. It is known that some of these stars are runaways, i.e. possess high space velocities (determined through the proper motion and/or radial velocity measurements), and therefore most likely were formed in embedded clusters and then ejected into the field because of dynamical few-body interactions or binary-supernova explosions. However, there exists a group of field O stars whose runaway status is difficult to prove via direct proper motion measurements (e.g. in the Magellanic Clouds) or whose (measured) low space velocities and/or young ages appear to be incompatible with their large separation from known star clusters. The existence of this group led some authors to believe that field O stars can form *in situ*. Since the question of whether or not O stars can form in isolation is of crucial importance for star formation theory, it is important to thoroughly test candidates of such stars in order to improve theory. In this paper, we examine the runaway status of the best candidates for isolated formation of massive stars in the Milky Way and the Magellanic Clouds by searching for bow shocks around them, by using the new reduction of the *Hipparcos* data, and by searching for stellar systems from which they could originate within their lifetimes. We show that most of the known O stars thought to have formed in isolation are instead very likely runaways. We show also that the field *must contain* a population of O stars whose low space velocities and/or young ages are in apparent contradiction with the large separation of these stars from their parent clusters and/or the ages of these clusters. These stars (the descendants of runaway massive binaries) cannot be traced back to their parent clusters and therefore can be mistakenly considered as having formed *in situ*. We argue also that some field O stars could be detected in optical wavelengths only because they are runaways, while their cousins residing in the deeply embedded parent clusters might still remain totally obscured. The main conclusion of our study is that there is no significant evidence whatsoever in support of the *in situ* proposal on the origin of massive stars.

Key words: Stars: early-type – stars: formation – stars: kinematics and dynamics – stars: massive – Magellanic Clouds – galaxies: star formation – galaxies: stellar content.

1 INTRODUCTION

One of the most important issues in the theory of star formation is the still incomplete understanding of how massive ($\gtrsim 10 M_{\odot}$) stars form (Zinnecker & Yorke 2007; McKee & Ostriker 2007). At least four theories have been developed,

the competitive accretion scenario (Bonnell, Bate & Zinnecker 1998; Bonnell, Vine & Bate 2004), collisional merging (Bonnell & Bate 2002), the single core collapse model (Krumholz & McKee 2008)¹, and the fragmentation-induced starvation model (Peters et al. 2010). It is therefore crucial to find conclusive constraints for the formation of massive

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¹ Note that models in which only massive stars form are idealised analytical descriptions or gas-dynamical simulations with highly unusual equations of state.

stars from observations. One important piece of evidence can be deduced from the formation sites of massive stars. While some theories need other stars and gas around the massive stars and predict their formation only within star clusters (competitive accretion, collisional merging, fragmentation-induced starvation), the core collapse model only needs a sufficiently massive and dense cloud core and allows for an isolated origin of O stars, at the expense of needing to postulate contrived initial conditions. Hence, analysis of O stars located in isolation is necessary to deduce whether or not they were formed *in situ* and thereby to narrow down the existing theories.

Several studies (e.g. de Wit et al. 2004, 2005; Schilbach & Röser 2008) searched for O stars in apparent isolation and tried to track down possible parent clusters. Although for most stars possible parent clusters were found, these studies also resulted in a number of candidate massive stars formed in isolation. These candidates are often treated as O stars formed in genuine isolation and thereby used to support one or another proposal on the origin of massive stars. For example, Krumholz et al. (2010) write “de Wit et al. (2004, 2005) find that 4 ± 2 per cent of Galactic O stars formed outside of a cluster of significant mass, which is consistent with the models presented here [...], but not with the proposed cluster-stellar mass correlation”. Similarly, Selier, Heydari-Malayeri & Gouliermis (2011) argue “there is [...] a statistically small percentage of massive stars ($\sim 5\%$) that form in isolation (de Wit et al. 2005; Parker & Goodwin 2007)”, and Franchetti et al. (2012) state that “Among the 227 Galactic O stars with $V < 8$, $\sim 83\%$ are in clusters, $\sim 10\%$ are runaways, and only $5 - 10\%$ are truly isolated (de Wit et al. 2004, 2005; Zinnecker & Yorke 2007). Therefore, about $10 \pm 4\%$ of core-collapse SNRs are not associated with other massive stars or star-forming regions [...]”.

The question whether O stars can form in isolation or not is important well beyond the topic of star formation. If massive stars need a clustered environment to form, star formation cannot be a purely statistical process as it would result in a non-trivial relation between the mass of a star cluster, M_{cl} , and the mass of the most-massive star, m_{max} , formed in this cluster (Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010). As galaxies with a low star-formation rate form only small star clusters (Weidner, Kroupa & Larsen 2004), which would not form any massive stars because of the $m_{\text{max}} - M_{\text{cl}}$ -relation, the integrated stellar populations (integrated galactic stellar initial mass function, IGIMF) of such galaxies could be quite different from the populations in individual star clusters (see Weidner & Kroupa 2005 and Kroupa et al. 2011 for details). Thus, the problem of isolated massive star formation remains highly relevant.

In this paper, we analyse if the known candidates for isolated massive star formation in the Milky Way and the Magellanic Clouds are actually unrecognised runaways and therefore were formed in the clustered way. Before discussing individual objects, we review the main mechanisms for the origin of runaway stars and methods for their detection, and briefly discuss the possible origin of low-velocity field O stars (Section 2). In Section 3 we discuss candidates for isolated massive star formation in the Milky Way, while those in the Magellanic Clouds are discussed in Section 4. We summarize and conclude in Section 5.

2 TWO SUBGROUPS OF MASSIVE FIELD STARS

Massive stars that are not members of any known star cluster, OB association or star-forming region are called field OB stars. Observations show that about 20 per cent of Galactic O stars are in the field (Gies 1987). It is also observed that massive stars in other (nearby) galaxies (Magellanic Clouds, M33, etc) sometimes lie outside star-forming regions (e.g. Madore 1978; Massey & Conti 1983; Kenyon & Gallagher 1985). Although the O star census in these galaxies is heavily incomplete, it is possible to estimate the percentage of their massive field stars through the distribution of Wolf-Rayet stars, the statistics of which is known much better. The Wolf-Rayet stars are only slightly older than their O-type progenitors, so that they should closely reflect the distribution of massive stars in their parent galaxies². The analysis of the distribution of Wolf-Rayet stars in the Magellanic Clouds and in M33 by Massey et al. (1995) and Neugent & Massey (2011), respectively, showed that the percentage of isolated Wolf-Rayet stars (and therefore that of isolated O stars) in these galaxies is comparable to that of the Galactic field O stars.

There are two subgroups of massive field stars: (i) OB stars with high (say $> 30 - 40 \text{ km s}^{-1}$; Blaauw 1961; Cruz-González et al. 1974) velocities (the so-called runaway stars; Blaauw 1961) and (ii) low-velocity OB stars. About 20–30 per cent of the Galactic field OB stars belong to the first subgroup (Blaauw 1961, 1993; Gies 1987). The typical space velocity of stars in this subgroup is several tens of km s^{-1} , although some of them possess much higher velocities, up to several hundreds of km s^{-1} (e.g. Gvaramadze, Gualandris & Portegies Zwart 2009 and references therein).

It is believed that runaway stars are formed in star clusters and then leave them because of two basic processes: (i) disruption of a short-period binary system following the supernova explosion (either symmetric or asymmetric) of one of the binary components (the so-called binary-supernova scenario; Blaauw 1961; Stone 1991) and (ii) dynamical three- or four-body encounters in dense stellar systems (the so-called dynamical ejection scenario; Poveda, Ruiz & Allen 1967; Gies & Bolton 1986). Obviously, some of the runaway stars could form due to the combination of these two processes, i.e. because of the dissolution of runaway massive binaries (Pflamm-Altenburg & Kroupa 2010; see also below).

The runaway stars can be revealed via several direct and indirect methods. The direct methods are based on detection of high ($> 30 \text{ km s}^{-1}$) peculiar transverse and/or radial velocities via proper motion measurements (e.g. Blaauw 1961; Moffat et al. 1998; Mdzinarishvili & Chargeishvili 2005) and spectroscopy (e.g. Massey et al. 2005; Evans et al. 2006, 2010), respectively. The indirect indications of the runaway nature of some field OB stars are the large (say $> 250 \text{ pc}$) separation of these stars from the Galactic plane (Blaauw 1961; van Oijen 1987) and the presence of bow shocks around them (Gvaramadze & Bomans 2008b; Gvaramadze et al. 2011c). Revealing runaways via the detection of their associ-

² Note that the Wolf-Rayet stars can be accelerated to much higher speeds than the O stars (Gvaramadze, Gualandris & Portegies Zwart 2008). Correspondingly, some of them can find themselves at much larger distances from their birth clusters.

ated bow shocks is especially helpful for those of them whose proper motions are still not available (e.g. in the Magellanic Clouds) or are measured with a low significance. The geometry of detected bow shocks can be used to infer the direction of stellar motion and thereby to determine possible parent clusters for the bow-shock-producing stars (Gvaramadze & Bomans 2008a,b; Gvaramadze et al. 2010a, 2011b,c; Gvaramadze, Kroupa & Pflamm-Altenburg 2010b; Gvaramadze, Pflamm-Altenburg & Kroupa 2011a).

There is, however, still no consensus on the origin of the low-velocity subgroup of the massive field stars. A significant fraction of these stars could be low-velocity runaways (e.g. Allison et al. 2010; Weidner, Bonnell & Moeckel 2011); note that the average escape velocity from the star cluster's potential well is comparable to the average peculiar radial velocity of the field O stars of $\sim 6.5 \text{ km s}^{-1}$ (Gies 1987). Others could originate because of rapid dissolution of star clusters following residual-gas expulsion at the very beginning of cluster evolution (e.g. Tutukov 1978; Kroupa, Aarseth & Hurley 2001; Boily & Kroupa 2003a,b; Goodwin & Bastian 2006; Weidner et al. 2007; Baumgardt & Kroupa 2007; Moeckel & Bate 2010). Moreover, some massive stars could be released into the field through the dissolution of runaway massive binaries following the supernova explosion of one of the binary companions (Pflamm-Altenburg & Kroupa 2010). The space velocity of the field stars produced in this process is the vector sum of the ejection velocity of the binary system, the orbital velocity of the star, and the kick velocity imparted to the star by the stellar supernova remnant (either neutron star or black hole) in the course of binary disintegration (Tauris & Takens 1998; Gvaramadze 2006, 2009). The resulting velocity would be small if its components effectively cancel each other.

3 GALACTIC CANDIDATES FOR ISOLATED MASSIVE STAR FORMATION

3.1 de Wit et al. sample of O stars apparently formed in isolation

In the study of Galactic field O stars by de Wit et al. (2004, 2005), three possibilities for their origin were considered. Namely, it was assumed that they are either (i) low-velocity runaways, (ii) unrecognised runaways, or (iii) members of unrecognised star clusters.

To check these possibilities, de Wit et al. used the catalogues of Galactic O stars to select those which are not members of any known cluster or OB association. It was found that ≈ 20 per cent (43 out of 193) of O stars with $V < 8$ mag are located in the field. For these stars de Wit et al. (2005) searched for known young (< 10 Myr) star clusters or OB associations within the projected distance of 65 pc (i.e. the drift distance which massive stars wandering with a peculiar transverse velocity of 6.5 km s^{-1} are likely to travel during their lifetimes). This search resulted in the detection of possible parent clusters for seven stars. Then, de Wit et al. (2005) excluded as field stars the possible runaways using the *Hipparcos* data, the radial velocity measurements and the distances from the Galactic plane. To address the third possibility, de Wit et al. (2004) searched for the presence of subparsec and tens of parsec scale clusters around all

43 field stars using their own deep infrared imaging and the Two-Micron All-Sky Survey (2MASS; Skrutskie et al. 2006), respectively. They found stellar density enhancements near five stars. One of these stars, HD 57682, has a large peculiar velocity (i.e. is a runaway star) so that the stellar density enhancement around it was interpreted as a statistical noise fluctuation (see also below).

Finally, de Wit et al. (2005) found that $\simeq 6$ per cent (11 out of 193) of O stars are not runaways and cannot be associated with previously unrecognized clusters, and therefore were probably formed *in situ*. Four of these eleven stars were regarded as “the best examples for isolated Galactic high-mass star formation” because of the presence of nearby indicators of recent star formation (H II regions, dark clouds, etc), so that the more conservative estimate of the percentage of stars formed in isolation is $4/193 \simeq 2$ per cent. Combining both estimates in a single one, de Wit et al. (2005) concluded that 4 ± 2 per cent of Galactic O stars “can be considered as formed outside a cluster environment”. This conclusion is often seen as ‘proof’ for the existence of isolated massive star formation or is used to support one or another proposal related to the problem of massive star formation (Parker & Goodwin 2007; Camargo, Bonatto & Bica 2010; Saurin, Bica & Bonatto 2010; Krumholz et al. 2010; Lamb et al. 2010; Franchetti et al. 2012).

3.2 Narrowing down the de Wit et al. sample

The percentage of O stars suggested by de Wit et al. (2005) to be formed outside a cluster environment could be reduced two times thanks to the study of Galactic field O stars by Schilbach & Röser (2008). These authors retraced the orbits of 93 O stars in the Galactic potential and found that six out of the eleven stars from the de Wit et al. sample originate in known young star clusters. One of these six stars, HD 123056, belongs to the group of the four stars considered by de Wit et al. (2005) as “the best examples for isolated Galactic high-mass star formation”. Moreover, Gvaramadze & Bomans (2008b) demonstrated that one more star from this group of four, HD 165319, is a bow-shock-producing (i.e. runaway) star, which most likely was ejected from the young massive star cluster NGC 6611. This latter discovery motivated us to search for bow shocks around the remaining four of the eleven O stars from the de Wit et al. sample that appear to be formed in isolation, namely, HD 48279, HD 124314, HD 193793, and HD 202124.

Our search for bow shocks was carried out by using the recently released Mid-Infrared All Sky Survey carried out with the *Wide-field Infrared Survey Explorer* (WISE; Wright et al. 2010). This survey provides images in four wavebands centred at 3.4, 4.6, 12 and $22 \mu\text{m}$ (with angular resolution of 6.1, 6.4, 6.5 and 12.0 arcsec, respectively), of which the $22 \mu\text{m}$ band is most suitable for detection of bow shocks (e.g. Gvaramadze et al. 2011c; Peri et al. 2012). Using the WISE data, we discovered a bow shock generated by one more star, HD 48279, from the group of “the best examples for isolated Galactic high-mass star formation” (see the left panel of Fig. 1 for the $22 \mu\text{m}$ image of this bow shock). This leaves us with three O stars apparently formed outside a cluster environment, so that the percentage of these stars is reduced to 1.0 ± 0.5 per cent (see Fig. 2 for the evolution of this reduction).

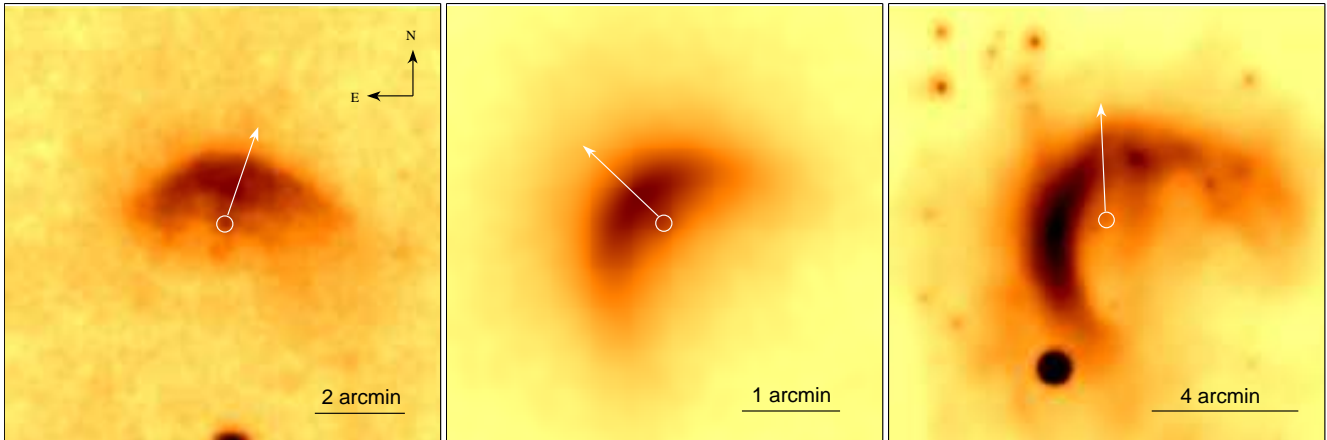


Figure 1. *WISE* 22 μm images of bow shocks associated with three field O stars: HD 48279 (left panel), HD 57682 (middle panel) and HD 153426 (right panel). The positions of the stars are marked by circles. The directions of the peculiar transverse velocities of the stars (derived from the new reduction of the *Hipparcos* data) are indicated by arrows. The orientation of the images is the same. See text for details.

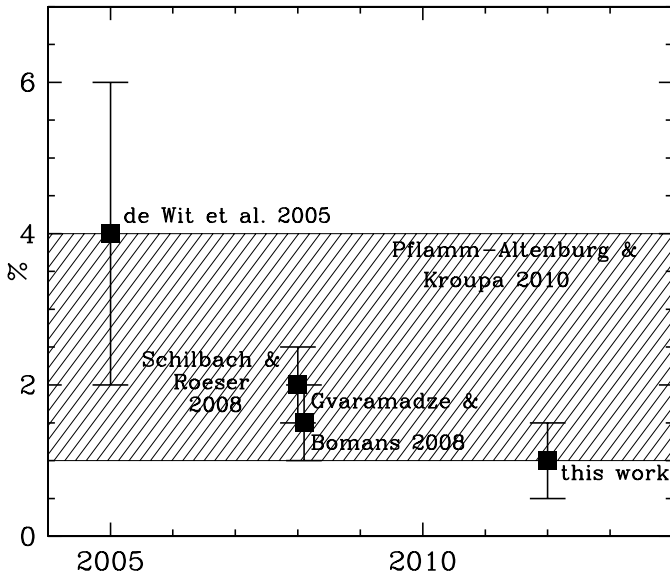


Figure 2. Evolution of the percentage of field O stars apparently formed in isolation with time. Data from de Wit et al. (2005), Schilbach & Röser (2008), Gvaramadze & Bomans (2008b), and this work. The current per cent of O stars apparently formed in isolation is fully consistent with what is expected (shaded area) from the two-step ejection mechanism for the origin of field O stars (Pflamm-Altenburg & Kroupa 2010). See text for details.

This small percentage of isolated O stars can easily be understood if one takes into account the fact that some massive stars can find themselves in the field because of the combined effect of dynamical ejection of massive binaries and their subsequent disruption following the supernova explosion of one of the binary components. The vast majority of field stars resulting from this *two-step ejection process* cannot be traced back to their parent clusters and therefore can be mistakenly considered as formed *in situ* (Pflamm-Altenburg & Kroupa 2010). It is important to note that the supernova explosion in a runaway binary can not only

re-direct or accelerate the companion star, but can also decelerate or even effectively stop it, so that the peculiar space velocity of the newly formed single field star could be much smaller than the ejection velocity of the runaway binary (Tauris & Takens 1998; Gvaramadze 2006, 2009). The obvious consequence of this effect is that the field *must contain* O stars, whose low space velocities are in apparent contradiction with the large separation of these stars from their parent clusters.

Moreover, some of the field O stars could be the products of the merging of the components of runaway binary systems. Imagine a tight binary (composed of two $10 M_{\odot}$ stars) ejected from a cluster with a velocity of 30 km s^{-1} . During the main sequence stage the binary components increase their radii several times so that the binary could merge into a single O star if the system was sufficiently tight³. If the binary merged after $\approx 20 \text{ Myr}$ since the ejection event (i.e. at a distance of $\approx 500 \text{ pc}$ from the birth place), the resulting rejuvenated star (blue straggler) would appear much younger than its parent cluster, while the cluster itself could be completely dissolved by that time.

The above considerations can explain the origin of single field O stars (unless the ejected systems were triple or of higher multiplicity; cf. Gvaramadze & Menten 2012). It turns out, however, that one of the remaining three O stars apparently formed in isolation, HD 124314, is a candidate single-line spectroscopic binary (Feast, Thackeray & Weselink 1955), while other one, HD 193793, is a massive binary composed of a WC7 and an O5.5 star (Fahed et al. 2011). Let us examine the possibility that both these systems are runaways, i.e. were dynamically ejected from putative parent clusters.

To check the possible runaway status of these two stars (HD 124314, HD 193793) and the third star (HD 202124) apparently formed in isolation, we determine their space velocities using proper motion measurements from the new

³ Note that in the course of dynamical ejection binary systems acquire high eccentricities (typically $\gtrsim 0.6$; Hills 1975; Hoffer 1983), which also facilitates the merging of binary components.

Table 1. Proper-motion measurements and heliocentric radial velocities (when available) for three O stars apparently formed in isolation (first three rows) and for three bow-shock-producing field O stars. For each star, the components of the peculiar transverse velocity (in Galactic coordinates), the peculiar radial velocity, and the total space velocity is calculated and added to the table.

Star	$\mu_\alpha \cos \delta^a$ mas yr ⁻¹	μ_δ^a mas yr ⁻¹	$v_{r,\text{hel}}$ km s ⁻¹	v_l km s ⁻¹	v_b km s ⁻¹	v_r km s ⁻¹	v_{tot} km s ⁻¹
HD 124314	-3.85 ± 0.87	-1.98 ± 0.69	–	14.6 ± 4.2	4.2 ± 3.5	–	$\geq 15.2 \pm 4.1$
HD 193793	-5.20 ± 0.37	-1.63 ± 0.33	–	7.2 ± 2.7	33.3 ± 2.8	–	$\geq 34.1 \pm 2.8$
HD 202124	-1.30 ± 0.57	-5.99 ± 0.45	-23.6 ± 3.3^b	0.9 ± 7.7	-39.4 ± 7.8	2.1 ± 3.3	-39.5 ± 7.8
HD 48279	-1.86 ± 0.83	2.73 ± 0.72	15.0 ± 5.0^c	-20.5 ± 5.8	3.4 ± 6.3	-19.6 ± 5	28.6 ± 5.4
HD 57682	10.46 ± 0.45	13.38 ± 0.34	23.0 ± 2.0^c	-23.2 ± 1.9	89.6 ± 2.2	-9.9 ± 2.0	93.1 ± 2.2
HD 153426	-0.58 ± 0.98	0.53 ± 0.54	-6.4 ± 5.0^c	19.2 ± 6.8	13.5 ± 7.7	18.3 ± 5.0	29.8 ± 6.4

^avan Leeuwen (2007); ^bKharchenko et al. (2007); ^cEvans 1967.**Table 2.** Details of three O stars apparently formed in isolation (first three rows) and of three bow-shock-producing field O stars.

Star	Spectral type	B^f mag	V^f mag	J^g mag	K_s^g mag	A_V mag	A_{K_s} mag	Distance kpc
HD 124314	O6 V(n)((f)) ^a	6.85	6.64	6.18	6.09	1.49	0.20	1.04
HD 193793	WC7+O5.5 ^b	–	–	–	–	–	–	1.67 ^h
HD 202124	O9.5 Iab ^c	8.06	7.82	7.18	7.09	1.54	0.20	3.20
HD 48279	O8 V ^d	8.04	7.89	7.65	7.69	1.30	0.11	1.64
HD 57682	O9 V ^e	6.23	6.42	6.81	6.94	0.25	0.05	1.11
HD 153426	O9 II-III ^a	7.61	7.47	7.06	7.01	1.24	0.17	1.94

^aWalborn (1973); ^bFahed et al. (2011); ^cWalborn (1971); ^dWalborn (1970); ^eJohnson & Morgan (1953); ^fMermilliod (1991); ^gCutri et al. (2003); ^hMonnier et al. (2011).

reduction of the *Hipparcos* data by van Leeuwen (2007). These measurements along with the heliocentric radial velocity of HD 202124 (taken from Kharchenko et al. 2007) are summarized in Table 1. To convert the observed proper motions and the radial velocity into the peculiar transverse and radial velocities of the stars, we used the Galactic constants $R_0 = 8.0$ kpc and $\Theta_0 = 240$ km s⁻¹ (Reid et al. 2009) and the solar peculiar motion $(U_\odot, V_\odot, W_\odot) = (11.1, 12.2, 7.3)$ km s⁻¹ (Schönrich, Binney & Dehnen 2010). The distances to HD 124314 and HD 202124 were determined using their B and V magnitudes from the Catalogue of Homogeneous Means in the UBV System by Mermilliod (1991), the J and K_s magnitudes from 2MASS (Cutri et al. 2003) (see Table 2 for a summary of these magnitudes), and the photometric calibration of optical and infrared magnitudes for Galactic O stars by Martins & Plez (2006). For HD 193793 we used the distance derived by Monnier et al. (2011) through spectroscopic and interferometric measurements of the orbit of this binary system.

The visual and K_s -band extinctions towards the stars (given in columns 7 and 8 of Table 2) were calculated using the relationships:

$$A_V = 3.1E(B - V), \quad (1)$$

$$A_{K_s} = 0.66E(J - K_s), \quad (2)$$

where we adopted the extinction law from Rieke & Lebofsky (1985) and the standard total-to-selective absorption ratio $R_V = 3.1$. The mean distances obtained from the optical and the infrared photometry are given in column 9 of Table 2.

The derived components of the peculiar transverse velocity in the Galactic coordinate system and the peculiar

radial velocity of HD 202124 are listed in columns 5, 6 and 7 of Table 1. For the error calculation, only the errors of the proper motion and the radial velocity measurements were considered.

It follows from Table 1 that HD 193793 and HD 202124 are running away from the Galactic plane and that their space velocities (see column 8 of Table 1) are > 30 km s⁻¹, so that both stars are runaways in the classical sense. It should be noted here that the non-detection of bow shocks around these stars does not contradict their runaway status. The point is that only a small fraction (≈ 20 per cent) of runaway OB stars produce (observable) bow shocks (van Buren, Noriega-Crespo, Dgani 1995). The most reliable explanation of this empirical fact is that the majority of runaway stars are moving through a low density, hot medium, so that the emission measure of their bow shocks is below the detection limit or the bow shocks cannot be formed at all because the sound speed in the local interstellar medium is higher than the stellar space velocity (e.g. Huthoff & Kaper 2002).

Table 1 also shows that the transverse peculiar velocity of the candidate single-line spectroscopic binary HD 124314 is well below 30 km s⁻¹. Since there are no reliable radial velocity measurements for HD 124314, one cannot exclude the possibility that this star is a runaway as well. On the other hand, HD 124314 is an O6 V(n)((f)) star, where ‘(n)’ refers to its fast ($v \sin i \simeq 250$ km s⁻¹; Penni 1996) rotation, which could be caused by the mass transfer in the close binary system. The natural consequence of the mass transfer is that the mass receiver not only spins up but can also be rejuvenated (e.g. Dray & Tout 2007), so that it would appear much younger than its actual age. If the rejuvenated

star (blue straggler) is a member of a runaway binary then the actual distance travelled by the system could be much larger than that inferred from the apparent age of the blue straggler and the peculiar transverse velocity of the system derived from proper motion measurements. Moreover, the absence of the secondary star contribution to the spectrum of HD 124314 might imply that the secondary is either a neutron star or a black hole (i.e. HD 124314 might be a post-supernova binary system). It is therefore possible that the space velocity of the binary was reduced (and re-oriented) due to the kicks caused by the mass loss from the system and the asymmetry of the supernova explosion (Stone 1982). In this case, the actual separation of the binary from the parent cluster could also be much larger than follows from the current (transverse) peculiar velocity and the apparent age of the rejuvenated star.

For the sake of completeness, we note that the use of the *WISE* data led to the discovery of bow shocks generated by two additional field O stars, HD 57682 and HD 153426 (see the middle and the right panels of Fig. 1), which, according to de Wit et al. (2004), are surrounded by stellar density enhancements. This discovery confirms the already known runaway status of HD 57682 (see Comerón, Torra & Gomez 1998) and implies that HD 153426 is a runaway as well. Moreover, one more field O star (HD 195592) associated with a stellar density enhancement is a known runaway and bow-shock-producing star (Noriega-Crespo, van Buren & Dgani 1997; Peri et al. 2012), so that at least three of the five stellar density enhancements detected by de Wit et al. (2004) around field O stars are noise fluctuations or chance superpositions.

Using the same procedure as for the three stars apparently formed in isolation, we calculated the distances to and the peculiar velocities of the three bow-shock-producing stars shown in Fig. 1 (see Tables 1 and 2). As expected, all three stars have space velocities large enough to classify them as runaways, while the orientation of their peculiar transverse velocities agree fairly well with the orientation of the symmetry axis of the bow shocks (see Fig. 1).

4 CANDIDATES FOR ISOLATED MASSIVE STAR FORMATION IN THE MAGELLANIC CLOUDS

The problem of isolated massive star formation was also widely discussed with regard to the Magellanic Clouds (Massey et al. 1995; Massey 1998; Oey, King & Parker 2004).

4.1 Very massive field stars in the Large Magellanic Cloud

The study of the massive star population in the Large Magellanic Cloud (LMC) by Massey et al. (1995) has shown that several very massive (O3–O4-type) stars are located at $\approx 100 - 200$ pc (in projection) from known star clusters and OB associations⁴. This finding was interpreted as indicating that the field can produce stars as massive as those

born in clusters (Massey et al. 1995; Massey 1998). In their reasoning, Massey et al. (1995) proceed from the general belief that most runaways originate in the course of disruption of massive tight binaries following the supernova explosion of one of the binary components (Blaauw 1961). From this it follows that an early-type massive star (such as an O3 or O4) would simply have no time to travel far from the birth cluster due to the youthfulness of this phase (Massey et al. 1995). Today it is known, however, that a more efficient channel for producing massive runaways is based on dynamical few-body encounters in the dense cores of embedded clusters (Poveda et al. 1967; Leonard & Duncan 1990; Clarke & Pringle 1992; Pflamm-Altenburg & Kroupa 2006; Gvaramadze & Gualandris 2011; Fujii & Portegies Zwart 2011; Banerjee, Kroupa & Oh 2012). In contrast to the binary-supernova ejection mechanism, the gravitational slingshot effect starts to produce runaways already in the course of cluster formation or at the very beginning of cluster dynamical evolution.

The large separations from the possible parent clusters and the young (≈ 2 Myr) ages of the very massive field stars imply that their (transverse) peculiar velocities should be as high as $\approx 50 - 100$ km s⁻¹ (Walborn et al. 2002)⁵, provided that these stars escaped into the field soon after the cluster formation. The runaway interpretation of the very massive field stars in the LMC received strong support after the discovery that some of them (including two O2-type stars, Sk-67°22 and BI 237, listed in Massey et al. 1995) indeed have such very high ($\approx 100 - 150$ km s⁻¹) peculiar (radial) velocities (Massey et al. 2005; Evans et al. 2010). Further support to the runaway interpretation of these stars comes from the detection of a bow shock around BI 237, whose orientation suggests that this O2 V((f*)) star (Massey et al. 2005) was ejected from the association LH 82 (Gvaramadze et al. 2010b; see also below).

There are three important issues that need to be kept in mind when assessing the likelihood of association between very young isolated massive stars and nearby stellar systems.

First, massive field stars might be blue stragglers dynamically ejected from their birth clusters. Some of them could already be formed in the parent clusters via merging of less massive stars in the course of close binary-binary encounters. The numerical experiments by Leonard (1995) showed that a significant fraction of such merger products is ejected into the field with peculiar velocities large enough to be classified as runaways. Moreover, dynamical encounters can also produce runaway binaries (e.g. Leonard & Duncan 1990; Kroupa 1998; Oh & Kroupa 2012), which then can produce blue stragglers by mass transfer or merging caused by stellar evolution (e.g. Gvaramadze & Bomans 2008a). Observations show that most O stars (both

⁴ In their footnote 5, Massey et al. (1995) list eight such stars; some of them were later re-classified as O2-type ones (Massey et al. 2005).

⁵ The large offsets from the parent clusters and the high peculiar velocities are not unusual for Galactic very massive field stars as well. For example, the bow-shock producing O4 If star BD+43° 3654 ejected from the Cyg OB2 association is located at ≈ 80 pc from the core of the association (Comerón & Pasquali 2007; Gvaramadze & Bomans 2008a), while its space velocity is ≈ 70 km s⁻¹ (Gvaramadze & Gualandris 2011). Other good examples of Galactic very massive field stars are two O2 If*/WN6 stars, which are located at $\approx 40 - 60$ pc in projection from their likely parent cluster Westerlund 2 (Roman-Lopes et al. 2011).

in clusters/associations and in the field) are binaries or higher-order multiples (e.g. Chini et al. 2012 and references therein). More importantly, $\approx 70 \pm 10$ per cent of runaway O stars are binaries as well (Chini et al. 2012)⁶. This fact along with the high proportion of massive binaries with short periods (Mermilliod & García 2001) and unit mass ratio (Pinsonneault & Stanek 2006; Kobulnicky & Fryer 2007) makes the rejuvenation process in runaway binaries common. From this it follows that the actual distances travelled by rejuvenated massive field stars might be much greater than those inferred from the apparent young ages of these stars and the assumed (plausible) ejection velocities.

We speculate that the ON2 III(f*) (Walborn et al. 2004) star [ELS2006] N11 031 (currently located within the confines of the OB association LH 10) might be such a runaway blue straggler. In Fig. 3 we show the Digitized Sky Survey II (DSS-II) red band (McLean et al. 2000) image of the star-forming region N11 (Henize 1956), which is the second largest H II region in the LMC after 30 Doradus. N11 is composed of several rich OB associations, two of which, LH 9 and LH 10, are outlined in Fig. 3 by dashed ellipses⁷. The radial velocity of [ELS2006] N11 031 is $\approx 30 \text{ km s}^{-1}$ greater than the median radial velocity of stars in N11 (Evans et al. 2006), which implies that this star might be a runaway. Moreover, [ELS2006] N11 031 is surrounded by a bow shock-like structure (see fig. 7a in Gvaramadze et al. 2010b), whose orientation suggests that [ELS2006] N11 031 is running away from the ≈ 3.5 Myr old (Walborn et al. 1999) massive compact cluster HD 32228⁸, which is located at ≈ 46 pc to the south of the star (see Fig. 3). If [ELS2006] N11 031 was indeed ejected from HD 32228, then it should be a blue straggler because its (apparent) age is about two times younger than that of the cluster. Correspondingly, the transverse peculiar velocity of [ELS2006] N11 031 should be $\geq 12 \text{ km s}^{-1}$.

Secondly, the presence of very massive stars in clusters and associations does not necessary mean that these stellar systems are as young as their most massive members (Gvaramadze & Bomans 2008a,b; Gvaramadze et al. 2011c). Some of these stars could be the merger products of dynamical few-body encounters (e.g. Portegies Zwart et al. 1999; Walborn et al. 1999), while others could be rejuvenated in the course of close binary evolution. Both processes can produce a wide range of apparent ages and can therefore explain the age spread often observed (e.g. Massey 2011) in star clusters and associations. Moreover, some relatively old OB associations could be ‘rejuvenated’ by young massive stars injected into these associations from nearby stellar systems (Gvaramadze & Bomans 2008a; Gvaramadze et al. 2011a).

Thirdly, it is well known that stars in the Milky Way typically form in dense embedded clusters (Lada & Lada 2003) with a characteristic radius of $\lesssim 1$ pc, which is independent of cluster mass (Kroupa & Boily 2002; Marks & Kroupa 2012). If star formation in other galaxies follows the same physics as it does in the Galaxy, then the known LMC clusters and OB associations should have been born from

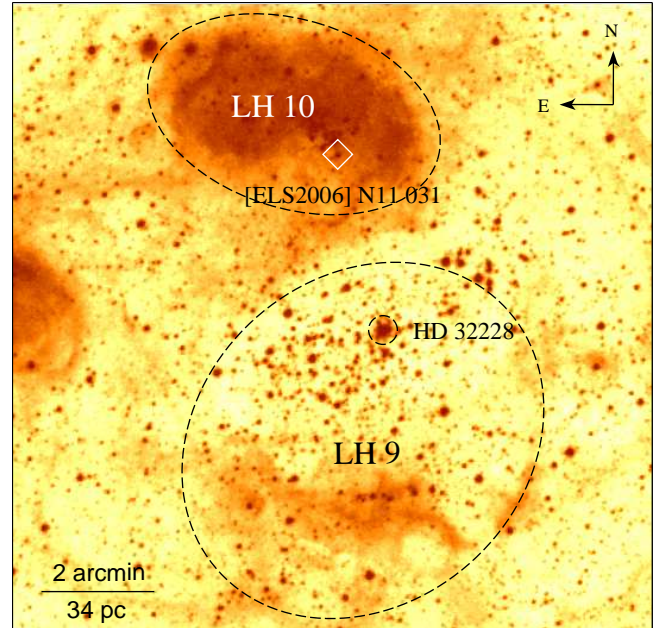


Figure 3. DSS-II red band image of the star-forming region N11 with the approximate boundaries of two rich OB associations, LH 9 and LH 10, indicated by dashed ellipses. The compact massive star cluster HD 32228 within the association LH 9 is indicated by a dashed circle. The position of the ON2 III(f*) star [ELS2006] N11 031 is marked by a diamond. See text for details.

configurations that are as dense as the embedded clusters in the Galaxy. A case in point is R136 which, like HD 32228, was, for a long time, thought to be a single very massive star, but is today known to be a compact very young massive star cluster (e.g. Weigelt & Baier 1985; Massey & Hunter 1998). Catching an embedded cluster which has a diameter smaller than a pc in the LMC would be difficult due to the high obscuration and compactness of such an object. Thus, it may even be that some of the isolated very massive stars may have been ejected from a compact embedded cluster which remains undiscovered. In other words, some massive stars can be detected in optical wavelengths only because they are runaways, while their cousins residing in the deeply embedded parent clusters might still remain totally obscured (see Gvaramadze et al. 2010a for possible Galactic examples of such runaways).

As mentioned above, the orientation of the bow shock around the O2 V((f*)) star BI 237 suggests that this star is running away from the association LH 82. To eject dynamically such a massive star, the association should initially contain a dense core of massive stars, which would currently be spread over the association. However, using the SIMBAD and the VizieR data bases we found only two known O-type stars within the confines of LH 82, of which the O2 III(f*) star (Walborn et al. 2004) Sk-67°211 is comparable in mass with BI 237. In Fig. 4 we present the DSS-II red band and the *WISE* 3.4 μm images of the field containing LH 82 and the two O2-type stars. One can see that these stars are located on the opposite sides of a dark lane (marked in the left panel of Fig. 4 by a small dashed circle), which coincides with a compact infrared nebula in the *WISE* image (see the right panel of Fig. 4). We propose that this lane might repre-

⁶ This observation clearly show that dynamical few-body encounters are the most important channel for production of runaways.

⁷ The approximate boundaries of these associations are taken from Bica et al. (1999).

⁸ Until relatively recently, HD 32228 was believed to be one of the brightest single stars in the LMC.

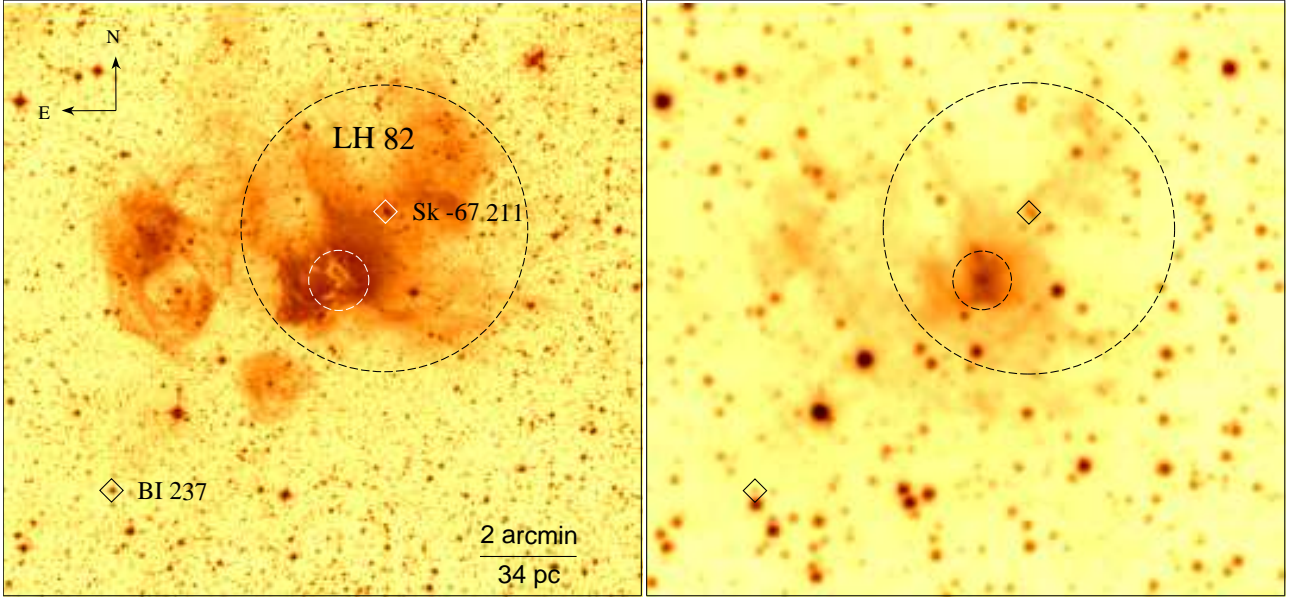


Figure 4. *Left:* DSS-II red band image of the field containing the association LH 82 (indicated by a large dashed circle) and two O2-type stars, BI 237 and Sk-67°211 (marked by diamonds). The position of a putative embedded star cluster is shown by a small dashed circle (see text for details). *Right:* WISE 3.4 μm image of the same field.

sent the parental cloud of a deeply embedded young massive cluster from which the two O2-type stars were dynamically ejected. If our proposal is correct, then the peculiar transverse velocities of BI 237 and Sk-67°211 should be ≈ 50 and 12 km s^{-1} , respectively, provided that both stars were ejected $\approx 2 \text{ Myr}$ ago. Using these estimates and the peculiar radial velocity of BI 237 of 120 km s^{-1} (Massey et al. 2005), one finds that the total space velocity of this star is $\approx 130 \text{ km s}^{-1}$ (cf. Gvaramadze et al. 2010b).

Recent numerical scattering experiments by Gvaramadze & Gualandris (2011) showed that three-body dynamical encounters between a massive binary and a single massive star can easily produce massive runaways with space velocities of $100 - 150 \text{ km s}^{-1}$. Moreover, N -body simulations of initially fully mass-segregated and binary-rich massive star clusters by Banerjee et al. (2012) clearly demonstrated that massive runaways represent the most probable type of runaways produced by such clusters (see also Section 4.4). These results provide a natural explanation of the origin of very massive field stars both in the Magellanic Clouds and in the Milky Way.

Although it was realised that most (if not all) isolated massive stars in the Magellanic Clouds could be runaways (Walborn et al. 2002, 2011; Foellmi, Moffat & Guerrero 2003; Massey et al. 2005; Evans et al. 2006, 2010; Brandl et al. 2007; Gvaramadze et al. 2010b, 2011a; Gvaramadze & Gualandris 2011; Fujii & Portegies Zwart 2011; Banerjee et al. 2012), the possibility of massive star formation outside of a cluster environment or in low-mass, sparse clusters remains discussed. Recently, several instances of isolated massive star formation in the Magellanic Clouds have been proposed in the literature (Lamb et al. 2010; Selier et al. 2011; Bestenlehner et al. 2011). Let us discuss them by turn.

Table 3. Eight isolated OB stars in the SMC (Lamb et al. 2010).

Star	Spectral type	v_r^a km s^{-1}	v_r km s^{-1}
[MLD95] SMC 16	O9 V ^a	121 ± 21	167 ± 11^d
AzV 58	B0.5 III ^a	146 ± 11	–
AzV 67	O8 V ^a	159 ± 13	179 ± 11^d
AzV 106	B1 II ^a	150 ± 12	–
AzV 186	O8 III((f)) ^b	159 ± 10	189 ± 7^d
AzV 223	O9.5 II ^c	189 ± 7	190^c
AzV 226	O7 IIIIn((f)) ^b	146 ± 21	208^c
AzV 302	O8.5 V ^a	161 ± 11	140 ± 9^d

^aLamb et al. (2010); ^bEvans et al. (2004); ^cMassey et al. (2009);

^dEvans & Howarth (2008); ^eEvans et al. (2006).

4.2 Lamb et al. sample of O stars formed in isolation

Lamb et al. (2010) considered a sample of eight isolated OB stars (see Table 3 for the list of these stars) in the Small Magellanic Cloud (SMC). To clarify the origin of these stars, Lamb et al. (2010) applied almost the same approach as de Wit et al. (2004, 2005), i.e. they searched for the presence of unrecognised clusters around isolated massive stars (using the *Hubble Space Telescope* imaging data) and searched for runaways among them through radial velocity measurements⁹.

Using the density enhancement and the ‘friends-of-friends’ algorithms (Davis et al. 1985), Lamb et al. (2010) detected sparse (approximately parsec scale) concentrations

⁹ The large distance to the Magellanic Clouds makes proper motion measurements difficult (see, however, de Mink et al. 2012), so that detection of high peculiar radial velocities remains the main tool for revealing runaways in these galaxies.

of low-mass stars around three target stars (AzV 67, AzV 106 and AzV 302), of which two detections (around AzV 67 and AzV 106) are marginal (see fig. 2 in Lamb et al. 2010).

Of the remaining five stars, two stars, [MLD95] SMC 16 and AzV 223, were identified as runaways because their radial velocities exceed by $> 30 \text{ km s}^{-1}$ the SMC's systemic velocity of 155 km s^{-1} (see column 3 in Table 3). This left Lamb et al. (2010) with three stars, AzV 58, AzV 186 and AzV 226, apparently formed in complete isolation. Assuming an isotropic distribution of runaway velocities, Lamb et al. concluded that these stars could be transverse runaways (i.e. runaways moving almost in the plane of the sky), but rejected this possibility because two of them were found to be located within H II regions in the line of sight (i.e. may still be in the regions of their formation). Recall that the same argument was used by de Wit et al. (2005) to define their four “best examples for isolated Galactic high-mass star formation”.

Based on the detection of sparse concentrations around three stars and on the apparently isolated formation of three other stars, Lamb et al. (2010) concluded that there is no physical $m_{\text{max}} - M_{\text{cl}}$ relation, the IGIMF can therefore not be different from the initial mass function on the scale of a whole galaxy and only core collapse models of massive star formation are able to explain these stars, but not the competitive accretion model. Below we show that these conclusions are unwarranted and that other much more likely possibilities to explain the origin of these stars do exist.

4.3 Narrowing down the Lamb et al. sample

First, we searched for alternative radial velocity measurements for all eight stars from the Lamb et al. sample using the VizieR data base¹⁰. We found measurements for six stars, three of which (see column 4 in Table 3) significantly differ from those reported by Lamb et al. (2010). This discrepancy could be interpreted as the indication that three stars from the Lamb et al. sample are binaries. On the other hand, it suggests that some of them might be runaways. Further spectroscopic monitoring of these stars is necessary to judge which of the two possibilities is correct. Note that the radial velocity measurement for AzV 223 by Massey et al. (2009) supports the runaway status of this star. Note also that AzV 226 is a fast-rotating star ($v \sin i \approx 300 \text{ km s}^{-1}$) so that the measurement of its radial velocity is less certain (Evans et al. 2006). Below we show, however, that the runaway status of just this star can be proven independently.

Then, we searched for bow shocks around all stars from the Lamb et al. sample using the $24 \mu\text{m}$ mosaic of the SMC obtained with the *Spitzer Space Telescope* within the framework of the *Spitzer Survey of the Small Magellanic Cloud* (S³MC; Bolatto et al. 2007). We found a bow shock around AzV 226 (see Fig. 5) and thereby prove its runaway status, which has already been suggested by the radial velocity measurement for this star (see column 4 in Table 3). This makes AzV 226 the third star in the Magellanic Clouds (besides of BI 237 and AzV 471; see Gvaramadze et al. 2010b, 2011a) whose runaway status was established through radial velocity measurements and detections of bow shocks. Recall that

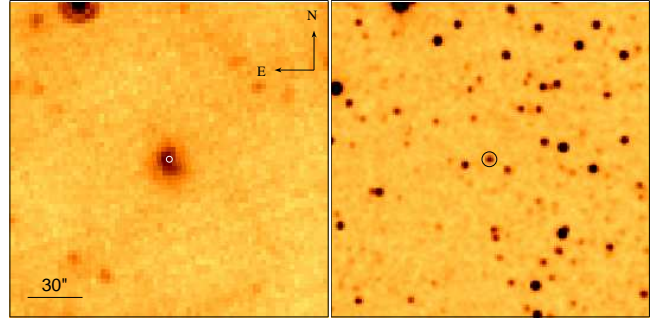


Figure 5. *Left:* *Spitzer* $24 \mu\text{m}$ image of the bow shock associated with the O7 III(f) star AzV 226. The position of AzV 226 is marked by a circle. *Right:* 2MASS J band image of the same field. At the distance of the SMC, 30 arcsec correspond to ≈ 8.6 pc.

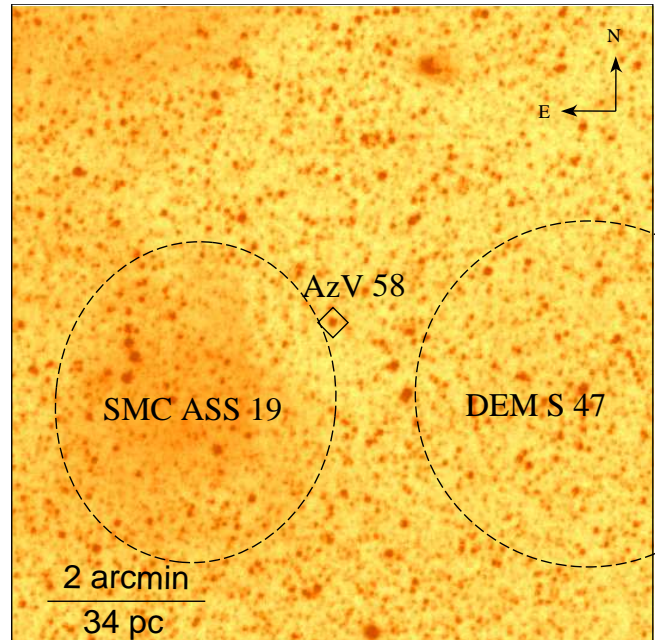


Figure 6. DSS-II red band image of the environment of AzV 58 (indicated by a diamond). The approximate boundaries of two nearby associations are shown by dashed ellipse and circle. See text for details.

the non-detection of bow shocks around other stars from the Lamb et al. sample does not exclude the possibility that they are runaways as well (see Section 3.2).

We found also that the B0.5 III star AzV 58 is located at the north-west periphery of the association SMC ASS 19¹¹ (see Fig. 6). The age of this association of ≈ 8 Myr (Chiosi et al. 2006) is comparable to that of AzV 58, which strongly suggests that SMC ASS 19 is the parent association of the star. One cannot also exclude the possibility that AzV 58 was ejected from the nearby ≈ 8 Myr old association DEMS 47.

However, there still remain two stars, AzV 106 and

¹⁰ <http://webviz.u-strasbg.fr/viz-bin/VizieR>

¹¹ The approximate boundaries of this and other associations shown in Figs. 6-9 were taken from the census of star clusters in the SMC by Bica & Dutra (2000).

AzV 302, whose radial velocities are comparable to the systemic velocity of the SMC, and which do not produce (visible) bow shocks. To these stars one also should add [MLD95] SMC 16, AzV 67 and AzV 186, whose runaway status remains unclear. One can envisage two possibilities to explain the origin of these stars.

First, they could either be (transverse) low-velocity or classical runaways. In the first case, the parent clusters or associations should be nearby. Using the SIMBAD data base¹², we found that the B1 II (Lamb et al. 2010) star AzV 106 is located ≈ 4.6 (or ≈ 80 pc in projection) from the association [B91] 9 (see Fig. 7). The age of this association of ≈ 8 Myr (Chiosi et al. 2006) is comparable to the age of the star. If AzV 106 is a former member of [B91] 9, then its peculiar transverse velocity is $\gtrsim 10 \text{ km s}^{-1}$, so that this star is a low-velocity runaway. We found also that the O8.5 V (Lamb et al. 2010) star AzV 302 is located not far (≈ 60 pc in projection) from the association SMC DEM 118 (see Fig. 8), whose age of ≈ 8 Myr (Chiosi et al. 2006) is twice the age of the star. AzV 302 therefore could be either a low-velocity rejuvenated star escaping from SMC DEM 118 (cf. Section 3.2) or an ordinary (transverse) runaway ejected from a more distant stellar system. Similarly, we found that AzV 67 is located at ≈ 90 pc in projection from the ≈ 10 Myr old (Chiosi et al. 2006) cluster [H86] 119, while [MLD95] SMC 16 and AzV 186 are located, respectively, at only ≈ 54 and 24 pc in projection from the centres of the ≈ 6 Myr old (Chiosi et al. 2006) associations [B91] 18 and [BS95] 83. Like AzV 302, these three stars could either be low-velocity rejuvenated runaways (if their possible binary status will be confirmed by follow-up observations) or ordinary runaways (if they originate in more distant stellar systems). For example, AzV 186 might have been ejected from the ≈ 5 Myr old (Chiosi et al. 2006) cluster NGC 330, which is located at ≈ 110 pc in projection from the star. In this case, the peculiar transverse velocity of AzV 186 should be $\gtrsim 20 \text{ km s}^{-1}$.

Secondly, it is also quite possible that the parent clusters of some of the five stars already dissolved, especially if these stars were formed in low-mass clusters with only a few or one massive star. Such clusters expel their gas rapidly, which results in the quick dispersal of the systems (see e.g. Kroupa & Boily 2002; Weidner et al. 2007; Baumgardt & Kroupa 2007). After the gas expulsion ≈ 90 per cent of the stars of the clusters would be expected to be distributed around the early type stars at distances of 10 to 50 pc (Weidner et al. 2011). Additionally, a far more extended population which could have travelled up to 1 kpc should have formed through dynamical few-body interactions in the clusters. And even if the clusters are still embedded in their natal gas clouds they are expected to loose up to 20 per cent of their stars due to dynamical interactions within 5 Myr and more if the objects are older (Weidner et al. 2011).

4.4 Two other candidates for isolated massive star formation

Recently, Selier et al. (2011) discussed one more candidate for isolated massive star formation in the SMC, namely, a O6.5-O7 V star powering the compact (≈ 2.2 pc in diameter)

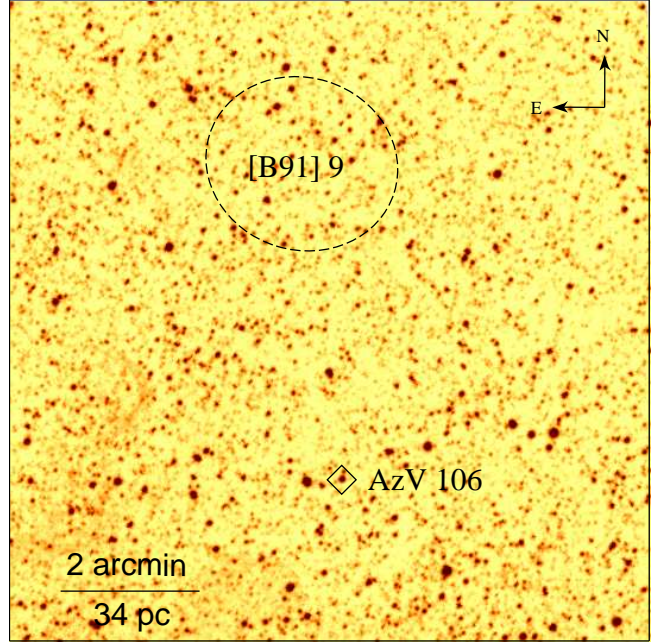


Figure 7. DSS-II red band image of AzV 106 (indicated by a diamond) and the association [B91] 9 (indicated by a dashed circle). See text for details.

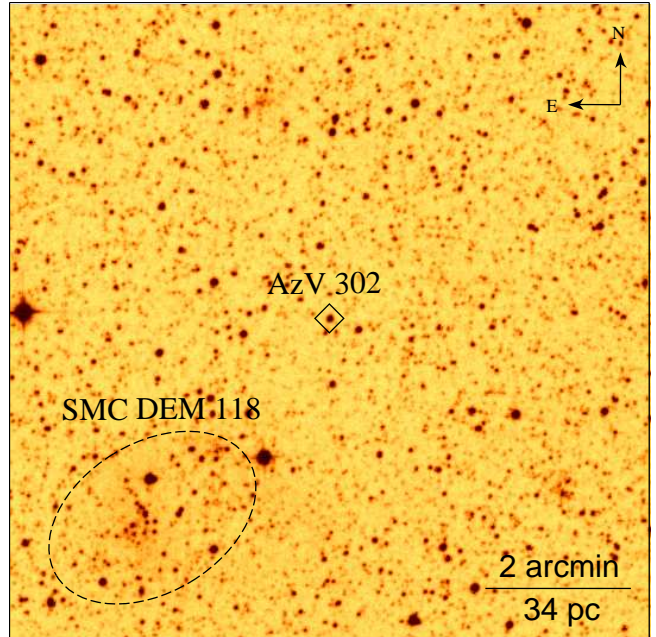


Figure 8. DSS-II red band image of the environment of AzV 302 (indicated by a diamond), with the position of the association SMC DEM 118 indicated by a dashed ellipse. See text for details.

H II region LHA 115-N33. Like de Wit et al. (2004), Selier et al. (2011) searched for a possible parent cluster to this star using optical images of a rather wide ($\approx 90 \times 90$ pc) field centred on the H II region. They did not find any statistically significant stellar cluster around the star, of size larger than 3 pc, which led them to believe that this star “represents an interesting case of isolated massive-star formation in the SMC”.

¹² <http://simbad.u-strasbg.fr/simbad/>

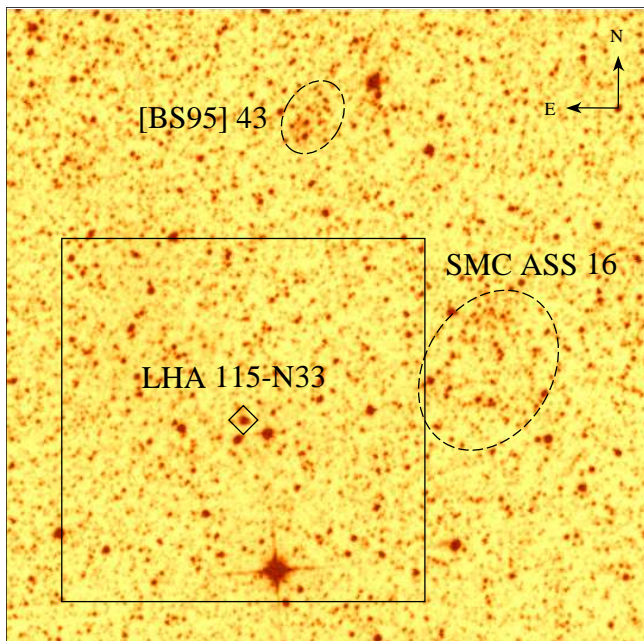


Figure 9. DSS-II red band image of the field around the H II region LHA 115-N33 (marked by a diamond). The $\approx 90 \times 90$ pc field centred on the H II region is shown by a square. The approximate boundaries of two possible birth associations to the star powering the H II region are shown by a dashed circle and an ellipse. See text for details.

However, using the SIMBAD data base we found two associations, SMC ASS 16 and [BS95] 43, located just outside the field examined by Selier et al. (2011) at ≈ 3.6 and 4.5 (or ≈ 61 and 77 pc in projection), respectively, from the H II region (see Fig. 9). Assuming that the star powering LHA 115-N33 was ejected from one of these young (≈ 4 and 6 Myr, respectively; Chiosi et al. 2006) associations, one finds that its peculiar transverse velocity should be $\gtrsim 12 - 15 \text{ km s}^{-1}$, which is a reasonable velocity.

In principle, Selier et al. (2011) do not exclude the possibility that the central star of the H II region LHA 115-N33 is a runaway. But as an argument against this possibility they offer the following reason: “it seems impossible that a massive star carries its H II region during the ejection”. On the other hand, they do not exclude the possibility that a runaway star was ejected into a molecular cloud, but noted that this situation “has never been encountered”. These two statements are incorrect.

In fact, it is known that any source of ionizing emission moving through the interstellar medium produces around itself a zone of ionized gas (i.e. an H II region) and that in the case of the supersonic motion the radius of the H II region is equal to the Strömgren radius (e.g. Tenorio Tagle, Yorke & Bodenheimer 1979). Whether or not such H II region would be observable depends on the number density of the ambient medium and on the total ionizing-photon luminosity of the star. In this connection, one can refer to fig. 5 in Gvaramadze & Bomans (2008b), which shows the bow-shock-producing

star HD 165319¹³ ejected from the star cluster NGC 6611 and currently powering the H II region RCW 158 (located ≈ 100 pc in projection from NGC 6611). Another good example of a massive bow-shock-producing star encountering dense material on its way through the field and powering an H II region is the well-known runaway star ζ Oph (Blaauw 1961; Noriega-Crespo et al. 1997; Hoogerwerf, de Bruijne & Zeeuw 2001) associated with the H II region Sh 2-27 (see Fig. 10).

Therefore it is highly likely that the massive star associated with LHA 115-N33 is a runaway ejected from one of the two nearby associations, which met a region of enhanced density (a cloud) on its way. The high number density of the cloud (380 cm^{-3} ; see Table 2 of Selier et al. 2011) implies that the bow shock generated by the star would be too compact to be resolved even with the *Spitzer Space Telescope*, which provides the best angular resolution ($6''$ at $24 \mu\text{m}$ or ≈ 1.7 pc at the distance to the SMC of 60 kpc) among the modern infrared space telescopes. Indeed, adopting the stellar mass-loss rate and the wind velocity typical of a O6.5-O7 V star of $\approx 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$ and $\approx 2500 \text{ km s}^{-1}$ (Mokiem et al. 2007), one finds that for any peculiar space velocity of the star the angular size of its bow shock would be at least two orders of magnitude smaller than the angular resolution of the *Spitzer* images (cf. Gvaramadze et al. 2010b).

More recently, Bestenlehner et al. (2011) reported the discovery of a very massive ($\sim 150 \text{ M}_{\odot}$) WN5h star, VFTS 682, located ≈ 30 pc in projection from the very massive star cluster R136 powering the giant H II region 30 Doradus in the LMC. Bestenlehner et al. (2011) convincingly showed that, like several other already known very massive runaways in the LMC (e.g. Evans et al. 2010; Gvaramadze et al. 2010), VFTS 682 could be a runaway, but unexpectedly concluded that the apparent isolation of this star may “represent an interesting challenge for dynamical ejection scenarios and/or massive star formation theory”.

It is worthy to note that VFTS 682 is not unique in its very high mass and the relatively large separation from R136. The very massive binary R145 (HD 269928), whose mass is of the same order of magnitude as that of VFTS 682 (Schnurr et al. 2009), is located ≈ 20 pc in projection from R136. The large offset of R145 from R136 could be interpreted as the indication that the binary was recoiled from the parent cluster due to an energetic three-body gravitational interaction in the cluster’s core and that a massive runaway star was ejected in the opposite direction (Gvaramadze & Gualandris 2011; cf. Fujii & Portegies Zwart 2011). Interestingly, such a star indeed exists just on the opposite side of 30 Doradus (see fig. 12 in Gvaramadze & Gualandris 2011). This star, Sk-69°206, located ≈ 240 pc to the west of R136, was identified as a runaway via detection of its associated bow shock, whose orientation is consistent with the possibility that Sk-69°206 was ejected from 30 Doradus (Gvaramadze et al. 2010b). Moreover, if one assumes that Sk-69°206 and R145 were ejected from R136 owing to the same three-body encounter, then the conservation of the linear momentum implies that the mass of Sk-69°206 should

¹³ Recall that this O9.5Iab star is considered by de Wit et al. (2005) as one of “the best examples for isolated Galactic high-mass star formation”.

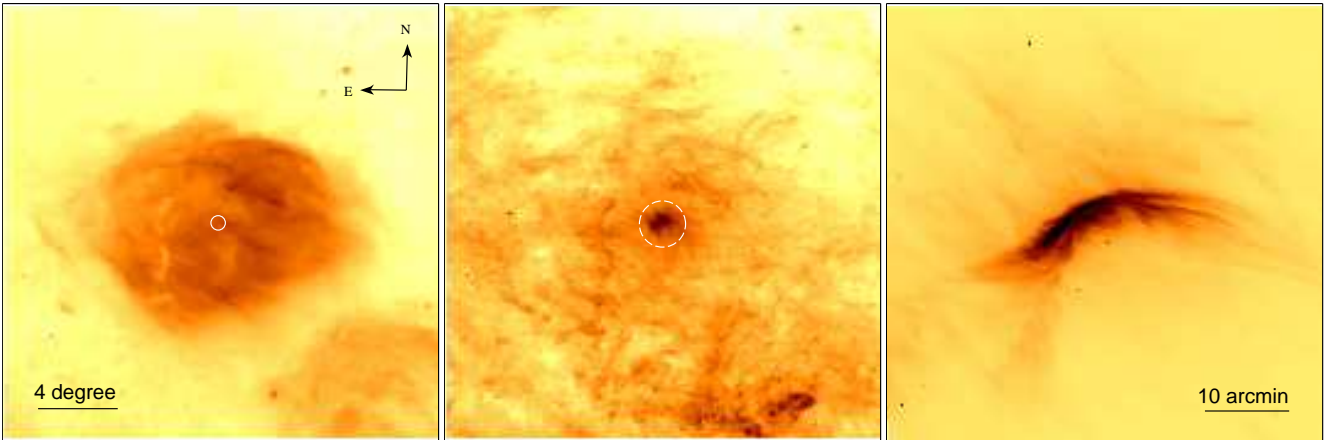


Figure 10. *Left:* $H\alpha$ image of the $H\text{ II}$ region Sh 2-27 taken from the Southern Hemispheric $H\alpha$ Sky Survey Atlas (SHASSA; Gaustad et al. 2001). The position of the ionising O9 V(e) star ζ Oph is indicated by a circle. *Middle:* *IRAS* $60\ \mu\text{m}$ image of the same field with the bow shock generated by ζ Oph indicated by a dashed circle. The images were generated by the NASA’s SkyView facility (McGlynn, et al. 1998). *Right:* *Spitzer Space Telescope* $24\ \mu\text{m}$ image (Program Id.: 30088, PI: A. Noriega-Crespo) of the bow shock around ζ Oph. The orientation of the images is the same.

be $\approx 10 - 15\ M_{\odot}$, which is consistent with the approximate spectral type of this star of B2 (Rousseau et al. 1978).

It is therefore likely that VFTS 682 is a former massive binary which was recoiled from R136 in the course of a strong dynamical three-body encounter in the dense core of R136 and merged into a single star (e.g. because of encounter hardening). The same conclusion also follows from high-precision N -body simulations of R136-like initially fully mass-segregated and binary-rich clusters (Banerjee et al. 2012), which show conclusively that dynamical ejections of very massive stars with kinematic properties similar to those of VFTS 682 are common, and that these very massive runaways represent the most probable type of runaways produced by such clusters.

5 SUMMARY AND CONCLUSION

In this paper, we examined claims of the existence of isolated massive star formation in the Milky Way and the Magellanic Clouds. These claims are often used to support the *in situ* proposal on the origin of massive stars. Our goal was to check whether the best candidates for isolated formation of massive stars are actually runaway stars, and therefore were formed in embedded clusters and subsequently ejected into the field because of dynamical few-body interactions or binary-supernova explosions.

Several indicators can be used to reveal the runaway status of the field O stars, namely, the high (say, $> 30\ \text{km s}^{-1}$) peculiar transverse and/or radial velocity of the stars or the presence of bow shocks around them. Detection of high radial velocities and/or bow shocks is especially useful for revealing the runaway status of distant stars, whose proper motion measurements are still not available (e.g. in the Magellanic Clouds) or are measured with a low significance. For Galactic candidates for isolated massive star formation (which are relatively nearby objects) the new

reduction of the *Hipparcos* data can also be used to search for their high transverse peculiar velocities.

Careful examination of the existing observational data showed that all but one of the best Galactic candidates for isolated massive star formation are in fact high-velocity and/or bow-shock-producing (i.e. runaway) stars. The only star, HD 124314, for which we derived a low peculiar (transverse) velocity and did not detect a bow shock¹⁴ is a candidate single-line spectroscopic binary. Thus, it is very likely that HD 124314 is a post-supernova binary system, which was dynamically ejected from the parent cluster and whose space velocity was reduced (and re-oriented) due to the kicks caused by the mass loss from the system and the asymmetry of the supernova explosion. Moreover, the mass transfer in the binary system prior to the supernova explosion might have significantly rejuvenated HD 124314, so that the actual distance travelled by this star could be much larger than that inferred from the apparent age of the star and its peculiar transverse velocity. Thus, HD 124314 might belong to a population of O stars (the descendants of runaway massive binaries) that *must* exist in the field and whose low space velocities and/or young ages are in apparent contradiction with the large separation of these stars from their parent clusters and/or the ages of these clusters, and which can be mistakenly considered as having formed *in situ*.

We also found that the candidates for isolated massive star formation in the Magellanic Clouds either possess high peculiar radial velocities (and therefore are runaways; one of these stars is associated with a bow shock as well) or are located not far from young stellar associations (and therefore might be runaways moving almost in the plane of the sky).

¹⁴ The non-detection of bow shocks around field stars does not exclude their runaway status, but could be caused by the motion of these stars through low-density, hot interstellar gas, which makes the bow shocks unobservable or even precludes their formation at all.

One of the latter stars, AzV 302, is about two times younger than the nearby association. This star could either be a rejuvenated low-velocity runaway or a high-velocity (transverse) runaway ejected into the field from a more distant stellar system. It is also possible that the parent cluster of AzV 302 (as well as the birth clusters of some other field O stars) already dissolved, especially if this star was formed in a low-mass cluster with only a few or one massive star. Such clusters expel their gas rapidly, which results in the quick dispersal of the systems. We argue also that some field O stars could be detected in optical wavelengths only because they are runaways, while their cousins residing in the deeply embedded parent clusters might still remain totally obscured.

The main conclusion of our study is that there is no significant evidence for massive stars formed in isolation. While it can never be proven to absolute certainty that a particular massive star was formed in a star cluster, the sum of the evidence, and in particular the known and well understood stellar dynamical processes, does not support isolated massive star formation as occurring.

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